RELIABILITY OF POLYCRYSTALLINE SILICON UNDER LONG-TERM CYCLIC LOADING

Joerg Bagdahn and William N. Sharpe, Jr.

Department of Mechanical Engineering, Johns Hopkins University, MD 21218-2681, USA
Phone: (410) 516-7554, Fax: (410) 516-4316, E-mail: bagdahn@titan.me.jhu.edu

ABSTRACT

The long-term mechanical behavior of 3.5 µm thick and 50 µm wide polysilicon tensile specimens under tension-tension cyclic loading was investigated. The initial fracture strength, σ_c, was 1.1 GPa. If the applied maximum cyclic stress was reduced by about 35 % to a value of σ_f = 0.75 GPa, the specimens failed after 10^8 cycles. No influence of frequency in the range of 50 to 1000 Hz was observed.

INTRODUCTION

During applications, polysilicon devices like gyroscopes, optical switches or micro mirrors are subjected to cyclic mechanical loading. The mechanical long-term reliability of materials is usually investigated using cyclic loading experiments. The number of cycles to failure, N, is determined for an applied maximum stress, σ_f, and N increases as σ_f decreases for most structural materials. However, since it is common to plot σ_f on the ordinate, one usually says that the fatigue strength decreases with increasing number of applied cycles.

Recent studies show a decrease of the fatigue strength during cyclic loading. Muhlstein et al. [1] and Kahn et al. [2] have reported fatigue results for notched polysilicon samples that were cycled at frequencies of 50 and 20 kHz respectively. Both found a reduction of the initial fracture strength by nearly 50% after 10^9-10^{11} cycles. In both cases the failure was initiated at a notch in the specimen. In addition, Kapels et al. [3] and Sharpe et al. [4] observed similar results for un-notched polysilicon tensile specimens at lower frequencies of 1 and 50 Hz. Muhlstein et al. [1] worked in the fully reversed mode (R = -1, ratio between minimum and maximum stress) whereas the other groups tested their material in the tension-tension mode with R~0. During all of these cyclic tests, a decrease of the fatigue strength with increasing number of loading cycles was found.

However the underlying basic microstructural processes responsible for the fatigue behavior are not completely known as yet. Van Arsdell and Brown [5] discussed a local slow crack propagation process based on stress corrosion of the native oxide at the polysilicon surface and a re-oxidation of the polysilicon at the crack tip. They measured slow crack growth rates in cyclically loaded samples (the same sample layout that was used by Muhlstein [1]) from the CRONOS MUMPs process, which were pre-cracked. They found for the pre-cracked samples with an applied stress intensity factor of K_I = 0.29 or 0.31 MPa$\sqrt{m}$ a steady-state crack growth rate of 1.9×10^{-12} m/s (75% relative humidity) or 1.4×10^{-13} m/s (50% relative humidity). Considering a fracture toughness of $K_{IC,crit}$ = 0.86 MPa$\sqrt{m}$, [6] the loading was about 35% of the critical loading. Allameh et al. [7] used an AFM to measure an increase of the roughness at the top surface in the vicinity of a notch with increasing of the number of cycles. This roughness increase might be generated due to a stress-assisted oxidation of the surface. In general, a roughness increase would reduce the strength of a brittle material significantly.

In the paper we describe the test methods and present results of cyclic loaded polysilicon tensile specimen that were fabricated by the MUMPs process.

EXPERIMENTAL

The samples were fabricated using the MUMPs process (run #36) at CRONOS. Figure 1 shows an overview of a chip with the tensile specimens. A scanning electron micrograph of a tensile test sample can be seen in Figure 2. The samples had gage section lengths of 250, 500, 1000 or 2000 µm. All samples were 50 µm wide and 3.5 µm thick. The gold lines on the gage section can be used to measure the strain directly during loading, which allows the determination of the Young's Modulus [8]. These lines were not used during this investigation.

The load is applied to the free paddle by gluing a thin fiber to it and connecting the other end to an external actuator. Before starting with the cyclic loading, tensile tests were performed on these specimens using a static tensile tester, which is described in [8].
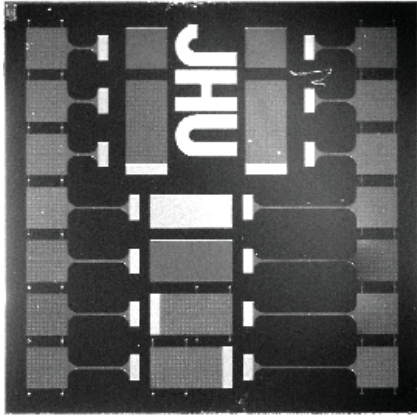

Figure 1: Optical micrograph of a 1 cm x 1 cm die with 14 test samples.
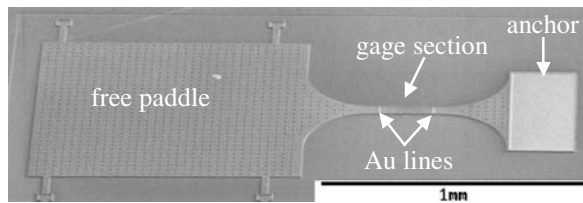

Figure 2: Scanning electron microscope images of a tensile specimen.

A die with the specimens on it was glued to a metal block, which was fastened directly to a piezoelectric load cell, for the cyclic tests. The load cell has a range of ± 50 N with a frequency response of ~ 1kHz. The other end of the fiber that was glued to the specimen paddle was connected to an actuator. The actuator is either a low voltage piezoelectric actuator or a small loudspeaker; both were used for tests at 50 and 200 Hz. Further tests at 1000 Hz were performed using only the piezoelectric actuator. A sinusoidal waveform is generated using a digital function generator. The tests were performed in tensile loading with a loading ratio of R~0, where R is the minimum load divided by the maximum load during cycling. The maximum stress during cycling loading (peak stress) was varied between 65 and 85 % of the previously measured average fracture strength of the polysilicon. A schematic of the test setup is shown in Figure 3.

The monitoring program, which is written in Agilent VEE, displays the waveform from the load cell and counts the cycles until the sample breaks. Figure 4 shows a typical signal output of the load cell at a test

frequency of 1 kHz. The maximum voltage of 1 V in Figure 4 refers to a force of 100 mN, which leads to a stress of 570 MPa in the sample.
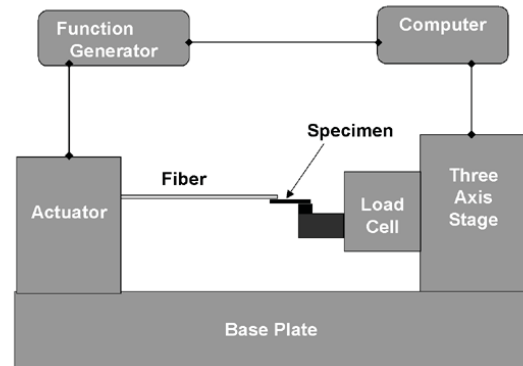

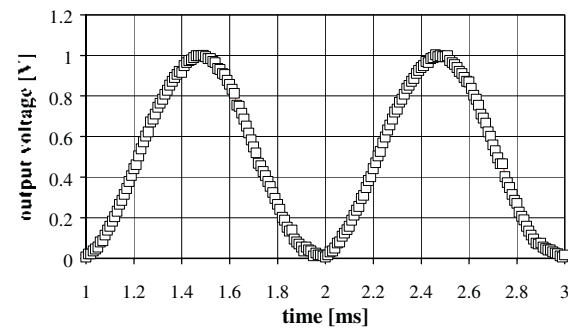Figure 3: Schematic drawing of the cyclic test setup

Figure 4: Load cell signal at a frequency of 1000 Hz.

RESULTS

Static and fatigue investigations

The mean fracture strength was $\sigma_c = 1.10$ GPa from 15 tested samples with a standard deviation of 0.07 GPa. No influence of the sample length on the strength was observed. However, due to the scattering of fracture tests of brittle material materials the testing of 3-5 samples per length is not sufficient for a statistical conclusion.

The cyclic investigations showed a decrease of the fatigue strength with increasing number of cycles. The results of the cyclic tests are plotted as peak stress versus the cycles (σ_f-N curve) in Figure 5. The results show that the fatigue strength of the polysilicon samples decreases from a mean tensile strength of $\sigma_c = 1.10$ GPa to about $\sigma_f = 0.75$ GPa after 10^8 cycles. No endurance limit (stress below which failure would never occur) was found during this investigation, which is in agreement with results from prior investigations [1,2,3]. It is obvious that no

influence of the frequency on the number of cycles to failure was observed. The time to failure depends on the frequency, so the samples tested at higher frequency fail after shorter times.
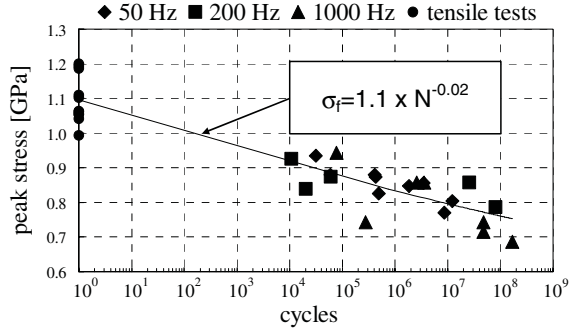

Figure 6: σ_f - N (stress-life) curve of polysilicon tensile specimens during cyclic loading tested with different cycling frequencies.

The experimental results can be fitted by a power law (line in Figure 6):

$$\sigma_f = \sigma_c \cdot N_f^m \qquad (1)$$

The number of cycles to failure can then be predicted by:

$$N_f = \left(\frac{\sigma_f}{\sigma_c}\right)^{1/m} \qquad (2)$$

A value of m = -0.02 were derived from the experimental results.

SEM and AFM Investigations

The anchored part of the specimen, which remains on the die after testing, was used for the SEM and AFM investigations.

The gage section part of the statically tested specimens normally disappears completely after failure. The SEM investigations revealed a probable failure initiation from the sidewalls of the sample or the sidewall and top surface corner when a part of the gage section remained. Figure 7 shows an example of such an investigation.

In contrast, the gage section normally remains on the die after the failure of the cyclically loaded samples. Furthermore, no influence of the deposited gold lines on the fracture initiation was observed. Figure 8 shows an overview and a higher resolution image of a cyclically loaded sample (peak stress 790 MPa, ~ 70% of the mean tensile strength) that failed after about 8 million cycles. In contrast to the statically

tested specimen, the sites of the fracture initiation at the sidewall and at the surface show a different morphology, which might be generated during the cyclic loading.
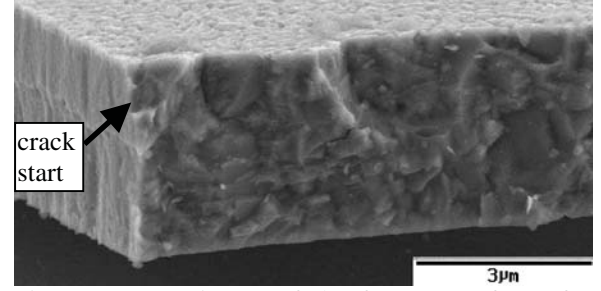

Figure 7: SEM image of the fracture surface of a statically tested sample. The failure probably initiated at the corner between the sidewall and the top surface.
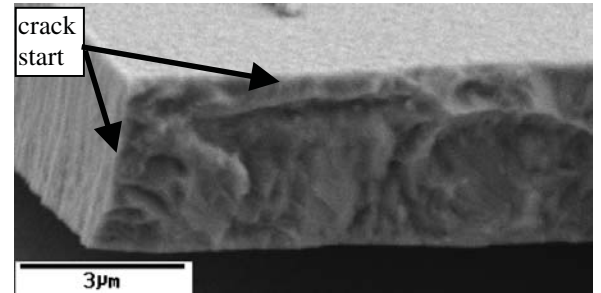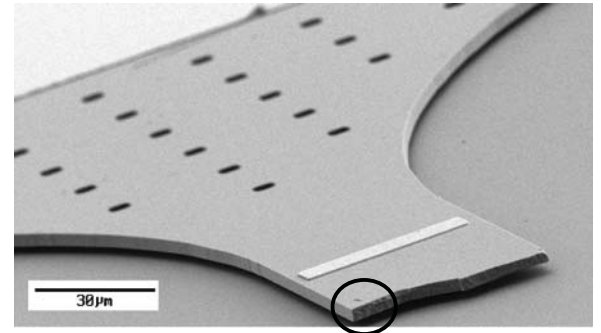

Figure 8: SEM images of a cyclically loaded sample (f=200 Hz) that failed after ~8 million cycles. The image at the bottom is a magnification of the area in the circle of the image above. The failure probably initiated from the sidewall.

In order to investigate the change of the morphology of the samples, AFM investigations were performed in an area of $10\mu m$ x $10\mu m$. Due to the alignment limitations of the AFM only roughness values of the top surface and not of the sidewalls could be measured. For the sample in Figure 8, an average roughness of $R_a = 17.2$ nm was determined on the top surface in the neighborhood of the fracture. In contrast, values of $R_a = 7.4$ nm and $R_a = 8.9$ nm were

measured on a part of the specimen subjected to small stresses and on a virgin sample.

DISCUSSION

The investigations revealed a decrease of the strength with increase of the number of cycles. No influence of the frequency in the range from 50 Hz to 1000 Hz could be found. The samples loaded with the higher frequency failed after shorter times, therefore the fatigue behavior cannot be explained by a simple stress corrosion model. The samples that are loaded with different frequencies should fail after the same time if the strength reduction is completely controlled by a stress corrosion crack growth [9]. This has been observed in cyclic loading of directly bonded silicon wafers [10]. It can therefore be concluded that processes other than stress corrosion are responsible for the strength reduction. The results from the SEM and AFM investigations revealed that during the cyclic loading experiments the material behavior in the neighborhood of the free surfaces (side walls and top surface) had changed. However, further work is required to understand the underlying microstructural processes.

For practical applications the results from these investigations cannot be directly used for a strength prediction of a component, since polysilicon has a size effect, which means the strength increases with decreasing surface area or volume [8]. However if the underlying microstructural reason for fatigue in polysilicon is the same for polysilicon from different fabrication sources and the fatigue effect itself is not influenced by the sample size, the results from fatigue test from different research groups should show the same strength decrease. In order to compare the results from [1,2,3,4] with the results from this paper the relative loading (peak stress divided by the initial strength, σ_f/σ_C,) was plotted versus the number of cycles. Interestingly, the results show the same relative strength reduction (Figure 9) and can be fitted by a power law, where the determined exponent m is the same as that derived from the results of this work (see Figure 6):

$$\frac{\sigma_f}{\sigma_c} = N_f^m \qquad\qquad (3)$$

Therefore, Eq. 3 should allow one to estimate the cycles to failure or the maximum peak stress for a required life if the initial strength is known. However, it should be considered that all results were derived using sinusoidal waveforms; other waveforms might change the behavior. In addition it has to be kept in

mind that the strength behavior in brittle materials shows a large scatter.
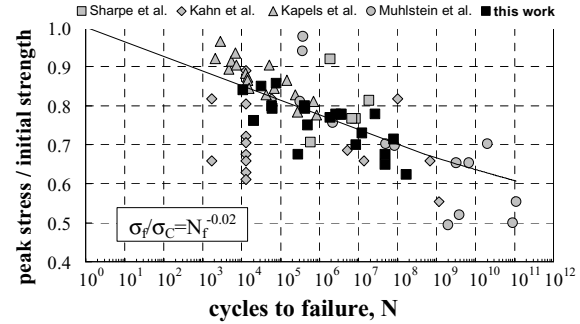

Figure 9: Overview of the fatigue behavior from different research groups.

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